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Original Research Paper

Impact of earthquake-induced bridge damage and time evolving traffic demand on the road network resilience

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HIGHLIGHTS

- Resilience quantification requires the use of a dynamic origin-destination matrix.
- Seismic losses mainly stem from travel time variations and trip cancelations.
- Indicators of functionality should be used for calibrating post-quake travel demand.
- Processing of real post-quake traffic data will improve the travel demand modeling.

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ABSTRACT

Damage from recent earthquakes has shown that substandard bridges are particularly vulnerable to strong ground motions being the weakest components of a road network. Structural and foundation damages in bridges lead to a significant loss related to both repair process and a prolonged traffic disruption, which in turn results in large indirect loss in the affected area. Along these lines, the estimation of the overall loss related to earthquake-induced damage in highway bridges and overpasses must be based on a wider network analysis rather than on a single structural assessment. Key concept in such a comprehensive loss estimation procedure is the network resilience, expressing the extent of both direct and indirect loss, as well as the system's ability to quickly recover its pre-earthquake state. In this paper, a recently developed framework for assessing the loss and resilience associated with seismic impact on the structural and geotechnical components of a road network, as well as the relevant software developed are extended to further consider the implications of post-earthquake traffic demand variation. Moreover, a sensitivity analysis is conducted for a case study network to investigate the impact of traffic demand variation after a major earthquake event and the subsequent trip cancelations on the time-variant, cumulative cost at a network level. The results clearly highlight that not only the seismic resilience of a highway network should be assessed in a holistic manner coupling seismic hazard, structural and traffic analysis, but the latter shall include realistic scenarios with respect to the potential variation of origin-destination demand after the earthquake and during the recovery period.

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1. Introduction

Strong earthquake events, including recent Sichuan in 2008, Chile in 2010 and Tohoku in 2011, among others, have shown that damage in a road network may substantially impair emergency response, rescue and recovery and lead to spatially and temporally extended traffic disruptions. In several cases, it was also noted that even minor damages had a disproportionately great impact to the network operation and to the total amount of earthquake induced monetary loss. Hence, a reliable assessment of the loss associated to road network damage and functionality is of paramount importance to the economic growth and sustainability of the community. In this context, bridges and overpasses are the most susceptible to seismic damage and as such, their failure can be usually considered as the primary source of loss (Kawashima and Buckle, 2013).

Loss due to future seismic events is quantified by means of seismic risk assessment that is generally based on the convolution of (a) the hazard of the area of interest (Han and Davidson, 2012; Sokolov and Wenzel, 2011), (b) the seismic fragility of the structures that are susceptible to earthquakes (i.e., their probability to exceed a certain degree of damage given an intensity measure) (Kwon and Elnashai, 2010) and (c) the exposure that refers to the expected consequences (Dorra et al., 2013; Kiremidjian et al., 2007a) given the hazard and the fragility. A number of studies have proposed frameworks for analyzing hazard, fragility and exposure of road networks and for combining them to assess the seismic risk of road networks (Chang et al., 2000; Dong et al., 2014; Günneç and Sibel Salman, 2011; Werner, 2000). Seismic hazard is usually accounted for by considering one or more seismic scenarios that either correspond to historical earthquakes (Kiremidjian et al., 2007b) or are developed by a regional hazard analysis methodology while fragility of bridges is derived explicitly for important structures (Stefanidou and Kappos, 2017) or is taken from precedent works for different structural typologies (Gidaris and Padgett, 2017; Kwon and Elnashai, 2010; Mackie and Stojadinović, 2005; Moschonas et al., 2009). On the other hand, consequence analysis required for defining the exposure of a road network greatly depends on the network resilience, the latter being defined as the network ability to withstand and adapt to a natural disaster, while being able to recover and restore the services offered quickly (Bruneau et al., 2003; Hosseini et al., 2016). The vastness of the resilience definition renders its quantification a complicated task, particularly in terms of indirect loss. Traffic analysis is also highly sensitive to the assumptions made with regard to post-earthquake traffic redistribution and the gradual restoration of the pre-event traffic conditions and demand.

Post-earthquake traffic redistribution is related to the fact that local damage even in a single bridge may influence, under circumstances, the functionality of the entire network. This means that after a strong earthquake the bridges stock, will be damaged and the associated roads may be partially or fully closed, hence, the travelers will be forced to seek alternative routes to accomplish their trips (Miller and Baker, 2016). These new routes will be probably slower than the pre-earthquake ones assuming that drivers commonly tend to pick the quickest route to a destination. Considering the increased travel time and the associated additional cost, some drivers may choose to postpone or even cancel their trip, head to emergency facilities, change destination or simply return home. Moreover, it is also probable that some network locations will be inaccessible anyway. The above reduced network functionality may in turn impede the emergency response, the recovery activities, the rehabilitation process the operation of energy facilities and the accessibility of critical transportation (ports, airports, train). There is strong interdependency therefore, between modern life activities which complicates seismic loss estimation (Lounis and Mcallister, 2016; Tapia and Padgett, 2016) as also highlighted by studies accounting for multiple dimensions of resilience (Bruneau et al., 2003; Cimellaro, 2016; Fiore et al., 2017; Nuti et al., 2010).

On the other hand, as the damage in the network bridges is restored gradually but not simultaneously, its spatial distribution also varies in time. As a result, the post-earthquake routes and the associated travel times ultimately depend on the speed and efficiency of the recovery activities (Alipour and Shafei, 2016). Moreover, as everyday activities rebound gradually and life comes back to normality, the post-earthquake demand also rebounds gradually. This time dimension of resilience implies that indirect loss, resulting from the variation of the transportation cost and the forgone trips, among others, is also a time-evolving quantity.

For these reasons, only a wider network perspective that includes the refined network and travel demand simulation as well a detailed flow estimation accounting for consecutive recovery phases can capture the time variation of the indirect loss and provide a reliable approach for its overall estimation, throughout the entire recovery period. Such an approach implies a high computational cost and most relevant efforts inevitably made a variety of simplifying assumptions. For instance, in some studies the evolution of the network functionality throughout the recovery period is neglected (Du and Peeta, 2014), while in others, the gradual network restoration is considered but the travel delays and the consequent indirect costs are only approximately estimated (Alipour and Shafei, 2016). Moreover, only Zhou et al. (2010) considered the post-quake travel demand variation. However, in this work, traffic rerouting after the earthquake is approximately

taken into account by assuming a residual capacity to the main network roads rather than by analyzing traffic on the basis of a refined network model.

Based on the above challenges and limitations, the scope of this paper is to expand an existing framework for assessing the risk and resilience of road networks to earthquake prone areas (Sextos et al., 2017b), in order to quantify the impact of the bridge damage on traffic routes, flows and speeds explicitly considering the post-earthquake demand variation. Considering a case study network tailored to the purposes of this study, four different assumptions are made regarding the traffic demand evolution from the onset of the earthquake to the end of the recovery period. Results highlight the influence of post-earthquake traffic demand modeling towards a reliable network resilience estimate. The key concepts and assumptions of the methodology developed are discussed in the following section.

2. Methodology

2.1. Spatial distribution of seismic damages

Fragility curves reflect the probability of exceeding predefined damage states (DS) for varying earthquake intensity levels that are expressed by means of an appropriate intensity measure (IM), such as peak ground acceleration (PGA) or spectral acceleration at the fundamental period of the structure (Sa_{T1}):

$$P_{S>DS_t/IM=im} = \Phi \left[\frac{1}{\beta_t} \ln \left(\frac{im}{im_{mt}} \right) \right] \quad (1)$$

where Φ is the standard normal cumulative distribution function, im_{mt} is the median threshold value of the IM associated with damage state t , β_t is the lognormal standard deviation of the IM associated with damage state t .

Assuming that DS_4 is the highest possible damage state of a bridge (i.e. DS_4 is the damage state corresponding to bridge collapse), the post-earthquake damage distribution within a network that is composed by a portfolio of I bridges, is represented by a damage vector, i.e., a column vector with I rows that relates each bridge with an integer d . The latter integer equals to $\{0, 1, \dots, 4\}$ for DS_0, DS_1, \dots, DS_4 where DS_0 denotes no damage. Given the fragility curves of the I bridges of a road network and a seismic map expressing the intensity measure distribution for an earthquake scenario, Eq. (1) is used for generating Monte Carlo samples of the damage vector. For a sample of the damage vector s , the integer d related to a specific bridge i with an intensity measure equal to im_i , is defined by the value a of a uniformly distributed random number within the range $[0,1]$, in respect to the probabilities of exceeding DS_1 – DS_4 :

$$d = \begin{cases} 4 & \text{if } a \leq P_{S>DS_4/IM=im_i} \\ 3 & \text{if } P_{S>DS_4/IM=im_i} < a \leq P_{S>DS_3/IM=im_i} \\ \vdots & \vdots \\ 0 & \text{if } a > P_{S>DS_1/IM=im_i} \end{cases} \quad (2)$$

Assuming the size of sampling S , a total number of S damage vector samples is formed for one intensity measure distribution (i.e., one seismic map).

2.2. Impact of bridge damage on the network performance

Seismic damage in a certain bridge may disrupt the vehicle passage over that bridge. In this case, the road segment along which the bridge is located (i.e. the part of a road between the two closest network intersections), is blocked from traffic. Usually, this traffic disturbance will last until the end of the restoration works on the damaged bridge. The required assignment of each network bridge to the road segment it belongs is performed by means of a correlation matrix. Naturally, each bridge is assumed to be assigned to a single road segment, while a road segment may be associated with zero, one or more bridges (i.e. more than one successive bridges are located along the particular road segment). A notable exception to the above “one bridge to one road segment” assignment, are the bridges that cross over a road segment, referred as overpasses. More specifically, damage in one overpass may also result in collapse to the undercrossing road segment. To account for this secondary impact of overpass damage to the network functionality, a second correlation matrix is defined, assigning each overpass to a crossed link. Moreover, it is assumed that after an earthquake, a road segment may either retain the 100% of its traffic carrying capacity (i.e., remain intact) or completely lose its traffic carrying capacity by being closed. Partial operation of the bridge is not accounted for due to the lack of clear circumstances under which such a decision would be made. The impact of seismic damage to the network operation is then defined in terms of traffic closure days using two restoration matrices. The first restoration matrix expresses the time required to repair different damage states (DS_1 to DS_4) for every bridge and overpass of the network (when bridge-specific fragility curves are used), or classes of structures with similar fragility. Similarly, the second restoration matrix expresses the duration of disturbance to the undercrossed roads due to collapse of an overpass.

Given the damage states of the I network bridges and overpasses defined by a sample of the damage vector, as well as the two correlation matrices and the two restoration matrices described above, a set of traffic closure time values is assigned to each network link j . The maximum of these values will define the closure time of the link itself, assuming that link j cannot be used by any vehicle until all the bridges and overpasses that affect it are fully restored. In this way, different closure times will be defined to every network link. Given the stepwise opening of the network links that results from this time- and spatial variant closure, several post-earthquake phases develop and evolve in time until the end of the recovery period.

2.3. Pre- and post-earthquake travel demand

Because of the relatively stable nature of the pre-earthquake traffic conditions, the drivers' behavior before the seismic event is assumed rather consistent and hence, it can be easily expressed in the form of a static origin-destination (OD) matrix format, which defines a traffic demand in terms of vehicles per hour for all the pairs formed among the network locations from which the drivers are originated or are heading to, e.g., cell in the i th row and j th column represents the number of vehicles that started from zone i with a destination of zone j (Zhou et al., 2010).

On the other hand, travel demand can be significantly altered immediately and for several days after a major earthquake event due to the emergency impact on the drivers' short and long term needs. For instance, business activity is expected to be reduced or reallocated after the earthquake. Moreover, as everyday activities rebound gradually and life comes back to normality, this altered post-earthquake demand also evolves in time. Post-earthquake demand variation immediately after an earthquake and its gradual restoration cannot be easily modeled because there is a lack of systematic data and analyses of road trips completed after real earthquakes, except for some satellite or remote sensing data that are still either not accessible or unprocessed at large in this regard.

The simplest rationale to address this problem would be to assume that the way in which traffic demand is altered at any time after an earthquake is a function of the network operation at any time instance, the variant destination needs and the updated traffic times themselves. The underlying difficulty in doing so is that traffic demand depends on the network condition (i.e. bridge structural health as well as, subsequent open and closed links) at every post-earthquake time instant considered, but at the same time depends on the associated travel times, which if increased, may yield an OD pair prohibitive. This observation is particularly true given the way in which real time navigation systems (e.g. Google maps) operate based on live traffic data sent by drivers using the service. It may well be the case that multiple drivers, in case of a suddenly closed road, may receive the same “optimum” alternative thus instantly overloading the suggested quickest route. For this reason, a user equilibrium model is needed to be integrated with a trip distribution (gravity) model, until an optimum solution is obtained through an iterative process (Zhou et al., 2010). To avoid such a computationally intensive process, we propose herein the update of the pre-quake demand by means of the network disruption index (NDI), an indicator that reflects the post-quake disturbance independently of the post-earthquake traffic quantities such as flows and travel times.

Network disruption index is a simplified indicator that reflects the network disruption or inversely, functionality, as a function of time. For a post-earthquake phase p derived according to the previous section, the network disruption index is defined as the sum of the importance factors of the links that remain functional, assuming that a link is non-functional either when it is closed (due to damage) or if it is intact but does not serve to any travels.

$$NDI_p = \sum_{j=1}^J NDI_{pj} \quad (3)$$

where

$$NDI_{pj} = \begin{cases} \gamma_j = \frac{V_{j0}}{\sum_{j=1}^J V_{j0}} & \text{if } j \text{ link is functional during phase } p \\ 0 & \text{if } j \text{ link is non-functional during phase } p \end{cases} \quad (4)$$

The importance factor γ_j of every network link is defined as the percentage of traffic load carried by link j under normal

conditions, that is, the ratio between its initial (pre-quake) traffic load V_{j0} and the total initial (pre-quake) traffic load $\sum_{j=1}^J V_{j0}$ of the entire network.

Network disruption index is calculated for every phase of the recovery period. Naturally, NDI takes a value in the range of $[0,1]$ right after the earthquake event and is restored back to 1 at the end of the last recovery phase. Given the first and the last day of each recovery phase and the corresponding NDI values, a graph such as the one shown in Fig. 1 is created. The length of every horizontal branch of this graph stands for one phase of the recovery period.

Having defined NDI on the basis of the importance factor γ_j and the operation of each link for every phase, the post-quake OD matrix for a phase p is derived by multiplying the origin-destination pair terms of the initial 2D pre-earthquake OD demand, with the value of NDI_p for each phase p . This practically implies that all OD terms, are uniformly reduced by a constant, importance-dependent factor which gradually restores to 1 increasing every time a closed highway network link is given back to traffic based on the assumed traffic closure days for every specific bridge or class. Notably, this approach only considers the trips forgone, neglecting the possible variation to the transportation needs and preferences for which complex models and data are needed.

2.4. Quantification of earthquake-induced loss to highway networks

Having clarified (a) the assumptions made to assess bridge fragility in section 2.1, (b) the mapping between bridge damage and network performance in section 2.2 and (c) the approach followed to update the OD matrix after an earthquake event (section 2.3) the seismic resilience methodological framework developed (Kilaniotis and Sextos, 2018) is presented in brief with emphasis on the new elements that are herein introduced.

The first step of the framework is the description of the highway network configuration in the form of a set of N nodes and J road links. The N nodes correspond to the network intersections and to the additional network points of interest that generate/attract trips (according to the available pre-quake OD matrix). The J links refer to the road segments that are defined by the nodes.

Next follows the definition of the location of the key network components, such as the I number of bridges (and

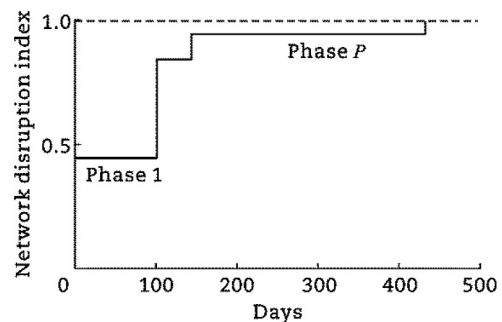


Fig. 1 – A sample “network disruption index-time” relationship.

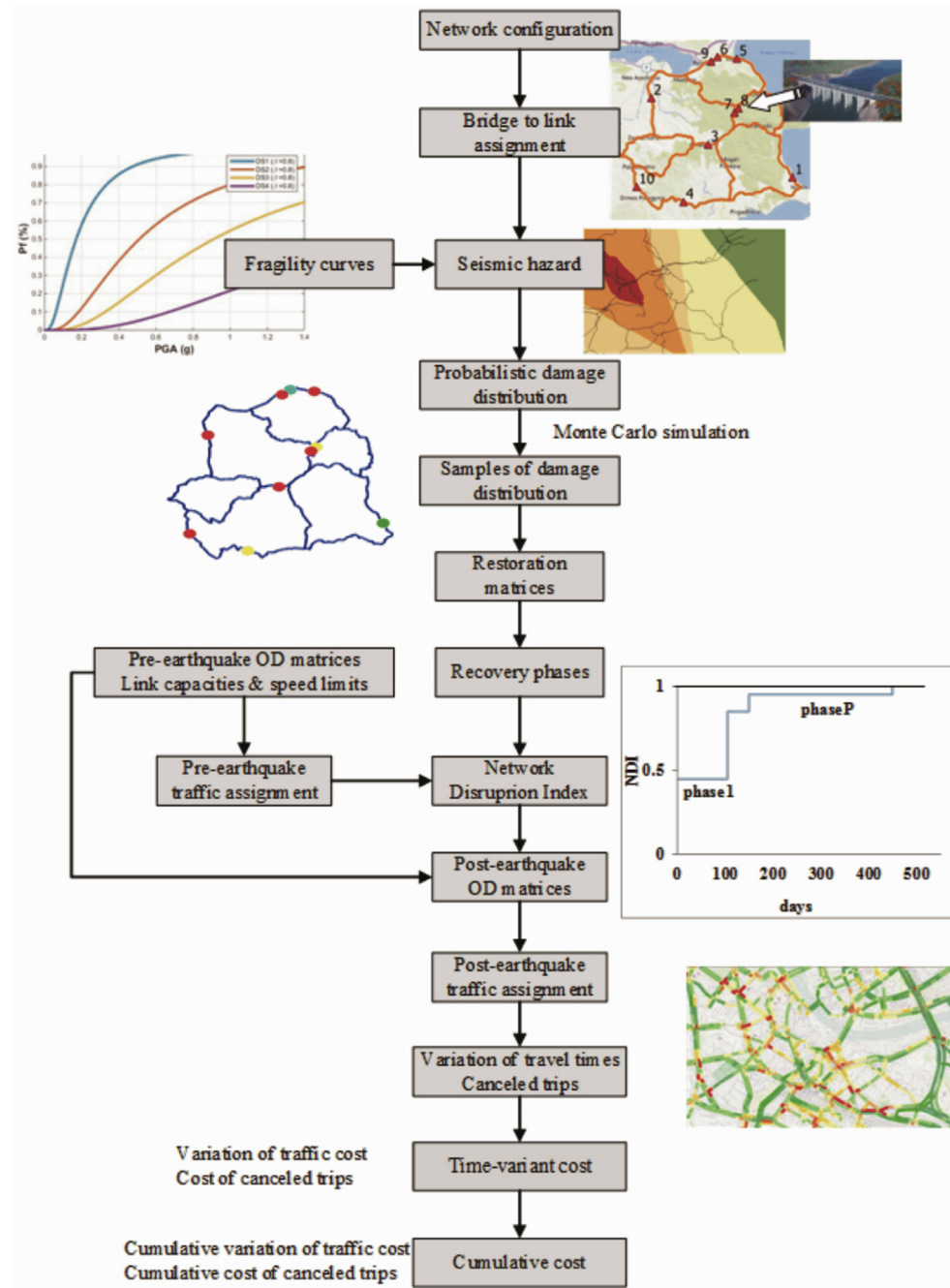


Fig. 2 – General workflow for estimating the impact of bridge and overpass damages to the time-variant and cumulative cost of an earthquake event.

overpasses) that may be affected by an earthquake. Note that in the general methodology, slopes and tunnels are also taken into consideration as long as their fragility can be provided using a compatible intensity measure.

Then, the regional seismic hazard is assessed according to an extension of the conventional probabilistic seismic hazard analysis (PSHA) that involves the discretization of the nearby active seismic sources into segments, the definition of seismic hazard levels with specific annual exceedance probabilities and ultimately, the generation of a number of probabilistic seismic maps (Kilaniotis and Sextos, 2018).

Subsequently, seismic susceptibility for each one of the I bridges (and overpasses) of the network is expressed in terms of fragility curves extracted from the literature or derived ad-hoc after detailed probabilistic assessment. Seismic maps and fragility curves are convoluted to estimate the probabilities of exceeding the different damage states for each bridge and overpass of the network. These probabilities are then utilized for generating S samples of the damage vector that deterministically defines the damage distribution in space (each sample defines a specific damage state for each bridge within the network).

In the following step, restoration matrices are defined. Given the restoration matrices and the link(s) affected by each damaged bridge or overpass, consecutive recovery phases for the entire recovery period and corresponding traffic scenarios are developed. Then, traffic carrying capacities and speed limits are defined for each network link while a pre-earthquake OD matrix, expressing the pre-earthquake traffic demand, is formed. In the next step pre-quake routes, flows and speeds are derived by an initial traffic assignment.

These traffic-related quantities are then utilized for calculating network disruption index for every recovery phase. Post-earthquake OD matrix for every recovery phase is defined by multiplying the pre-earthquake OD matrix with the corresponding value of the network disruption index as discussed in section 2.3. Subsequently, traffic assignment for each one of the post-quake traffic scenarios is performed and the corresponding travel time variation and the number of cancelled trips are derived.

Cost due to travel time variation and cancelled trips is then estimated for expressing the time-variant earthquake impact in terms of variation of traffic cost and cost of cancelled trips, respectively. In the final step, cumulative earthquake cost (Sextos et al., 2017b) considering both the direct (i.e., due to structural damage) and the indirect (i.e., due to additional traffic time) cost is calculated for assessing the loss throughout the entire recovery period. The general workflow for estimating the impact of bridge and overpass damage to the time-variant and cumulative cost of an earthquake event on the network is illustrated in Fig. 2. The software developed for materializing the methodology into a GIS-based decision-

making tool is briefly presented in section 3. The main difference of the approach followed herein with respect to the above methodology is that the OD is not taken constant but is assumed to evolve after the main shock and during the recovery period. In fact, four different assumptions of this dynamic OD are parametrically investigated in section 5.

3. Software development

3.1. Computational workflow

The above framework is materialized as a standalone, GIS-based interactive freeware that is based on the software of the initial framework (i.e., without post-earthquake traffic demand variation). As shown in Fig. 3 the use of the software requires some preliminary work to be done in advance. This includes the data collection, the processing of the collected data as required for the software use and ultimately, the appropriate sorting of the input data in a shape file (.shp) and in several spreadsheet files. The algorithm is implemented in Matlab GUI except for the traffic assignment and analysis that is performed by means of the open-source traffic assignment engine DTALite (Zhou et al., 2014). The latter is fully incorporated into the developed software. In particular, during runtime, Matlab code generates a number of .csv files defining both the pre- and post-earthquake traffic scenarios and triggers the DTALite execution.

Subsequently, DTALite runs multiple analyses in the background in batch mode and computes the traffic routes, flows and speeds for both the pre-earthquake network state

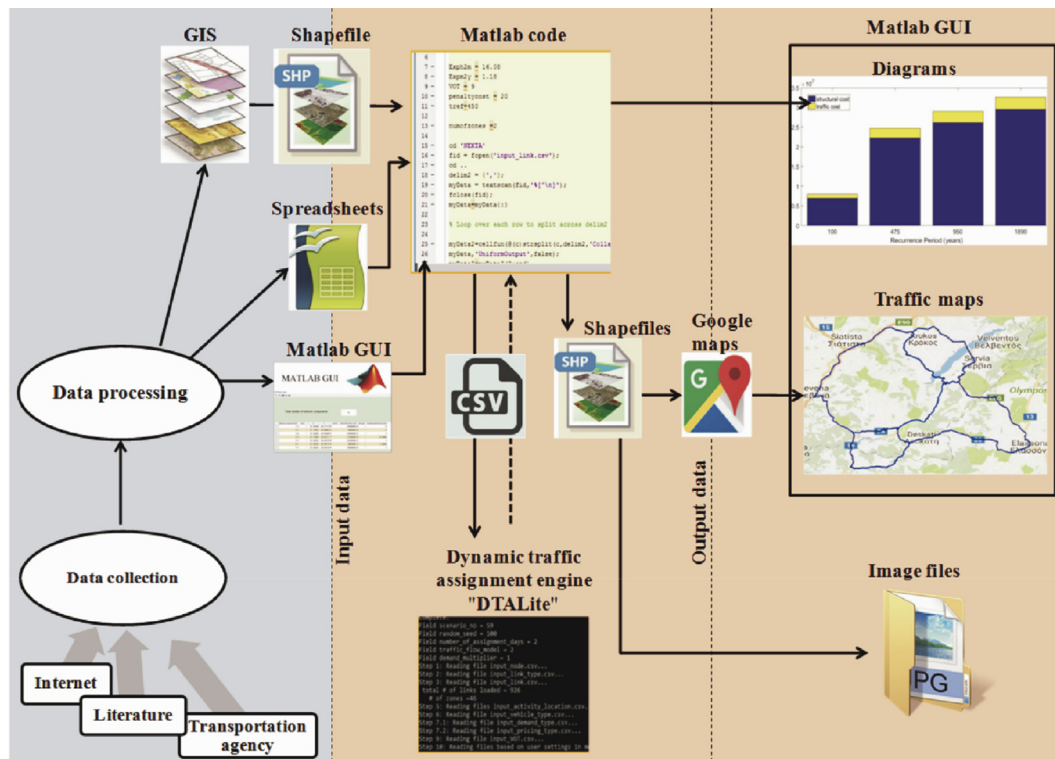


Fig. 3 – Computational framework for implementing the proposed framework.

and the post-quake traffic scenarios. DTALite results are then saved in a new.csv file that is automatically read by the Matlab code. Results include a number of traffic maps and diagrams. Traffic maps indicate the routes that the vehicles follow before the earthquake and during each recovery phase and can be projected over a Google map layer if internet access is available. Diagrams show the time-variant and cumulative variation of the cost due the modification of the travel times and the trip cancelations following an earthquake. All the results are shown in the Matlab User Interface and are also automatically stored into image files for further use.

3.2. GIS-based network modeling

The implementation of the proposed framework with the aid of the software requires the use a GIS platform (e.g., QGIS, Arcgis). More specifically, existing road maps are used for identifying network nodes. Each node is assigned with a unique ID number and the corresponding geographic coordinates. Given the nodes, the road network is then discretized into links. Each network link is defined by the pair of nodes located at its edges and is assigned with a unique ID number.

With the aid of a GIS platform network nodes and links are digitized in the form of a nodal and a polyline GIS vector, respectively. As shown in Fig. 4, an attribute table is created for defining the IDs and the edge nodes IDs of the network links as well as the length, traffic capacity and speed limit of the corresponding road segments. The nodal vector, the polyline vector and the attribute table are saved in the shape file (.shp) that, as it was mentioned in the previous section, is used as input to the software.

Matlab code including a GUI, QGIS and DTALite traffic assignment engine are all freely available and consist a ready-to-use computational package that is made available to the engineering community (www.retis-risk.eu). It is also noted that the above automation not only permits the application of

the methodology developed but permits informed decision-making by the stakeholder through the execution of alternative scenarios for resilience improvement by selective bridge retrofit activities or improved recovery plans (Sextos and Kilanitis, 2018).

4. Case study

4.1. Network configuration, traffic data and critical components

To investigate the importance of post-earthquake traffic demand on the overall resilience of the network, the framework described in the previous sections was applied for the case of a sample road network. Its topology corresponds to a real network in Greece (Sextos et al., 2017a) and it is modeled by 12 nodes and 34 unidirectional links, as shown in Fig. 5. Each unidirectional link is denoted by the IDs of the two nodes that it connects (e.g., link 1-2 implies traffic from node 1 to node 2). It is noted that the two links associated to the two directions (i.e., branches) of a road connecting a node pair (e.g., links 1-2 and 2-1), are assumed to have the same length, traffic carrying capacity and speed limit. The network consists of 200 km of highways and 120 km of secondary roads in total. The speed limit is considered to be 120 km/h for highways and 60 km/h for secondary roads. Similarly, a traffic capacity of 3600 and 1800 cars per hour is assumed for the first and the latter, respectively. The network functionality depends on the potential seismic damage of 8 pairs of bridges (for bi-directional traffic) and 2 pairs of tunnels.

Each pair of bridges or tunnels consists of similar and nearby but distinct and structurally independent structures (e.g. two structurally independent branches of a bridge) while each component affects only the functionality of the

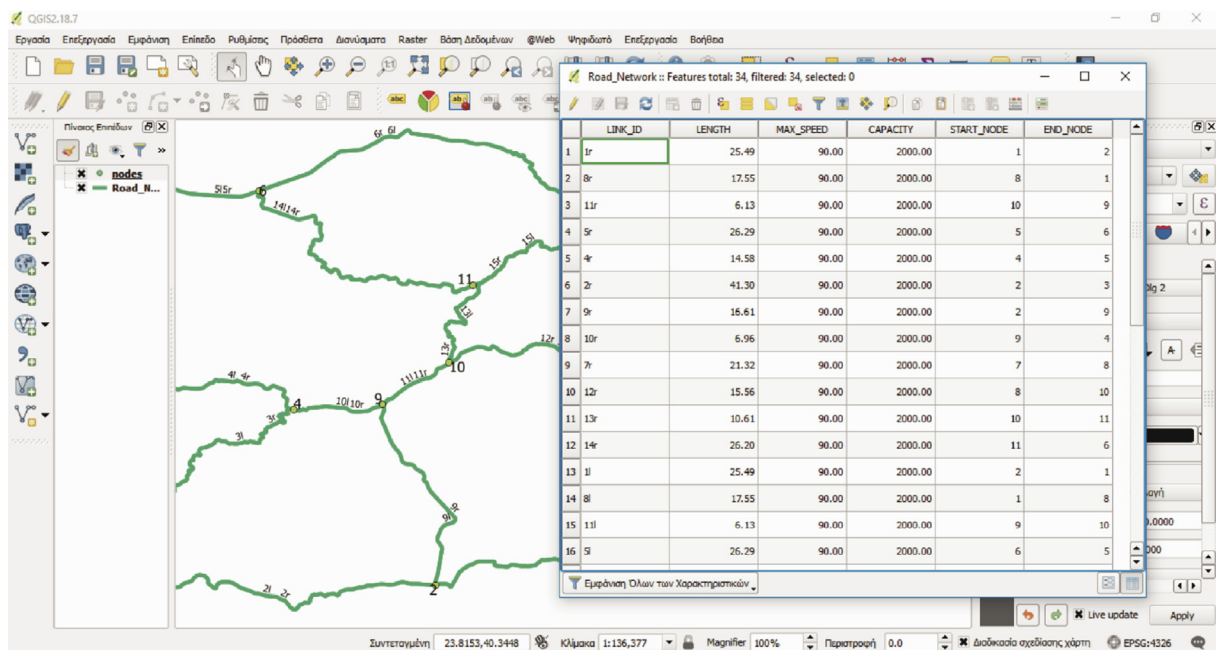


Fig. 4 – GIS graphical display of the nodes and the links and the associated attribute table for a sample road network.

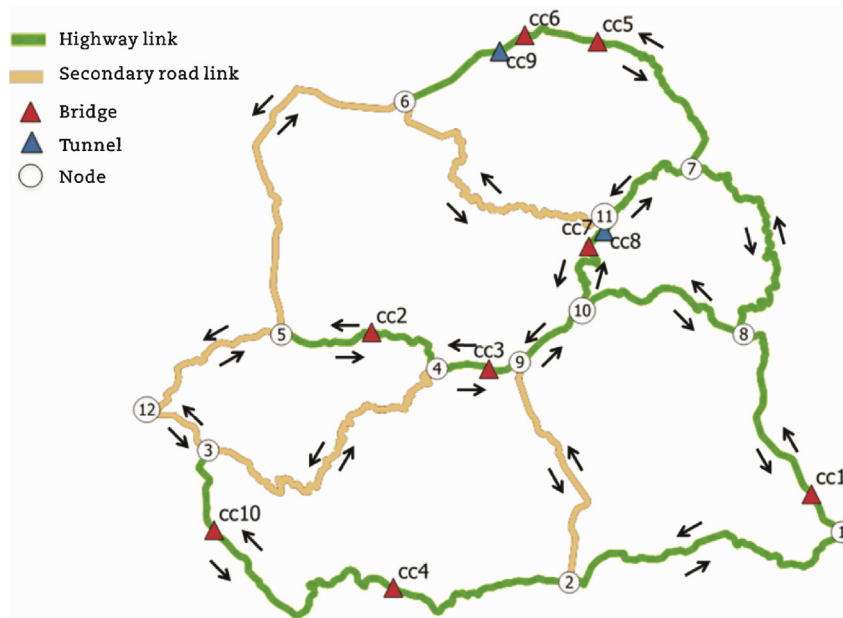


Fig. 5 – Network configuration, traffic data and critical components of the case study network.

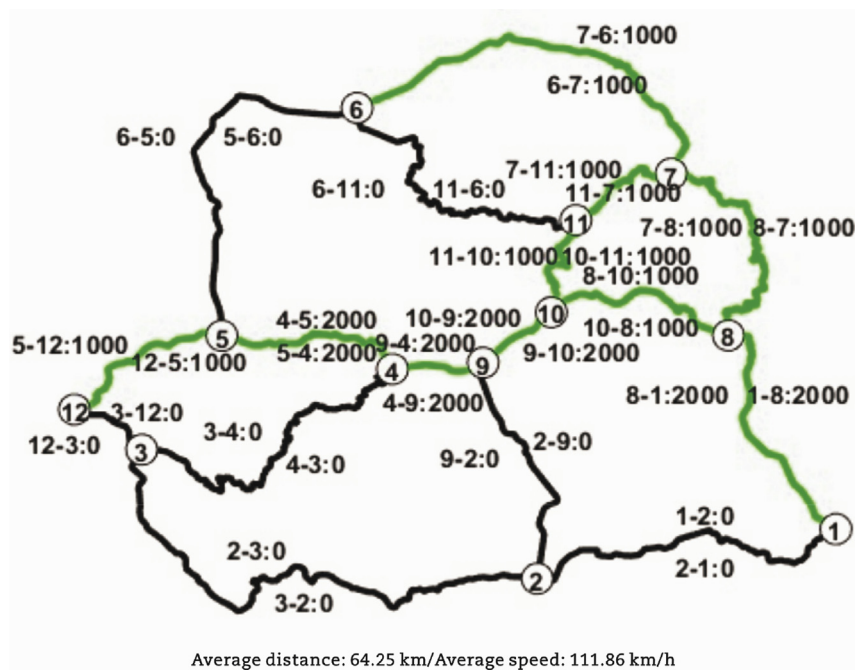


Fig. 6 – Pre-quake routes and flows.

Table 1 – Classification of the critical components to fragility classes and values of the corresponding the im_{mt} and β_t parameters.

Class ID	Type	Critical components	DS ₁		DS ₂		DS ₃		DS ₄	
			im_{mt}	β_t	im_{mt}	β_t	im_{mt}	β_t	im_{mt}	β_t
1 MSC concrete	Bridge	cc1, cc7, cc10	0.16	0.70	0.53	0.70	0.75	0.70	1.01	0.70
2 MSSS concrete	Bridge	cc3, cc4, cc5	0.22	0.80	0.69	0.80	1.31	0.80	3.39	0.80
3 Box MSSS slab	Bridge	cc2, cc6	0.17	0.80	0.51	0.80	0.91	0.80	1.87	0.80
4 Standard	Tunnel	cc8, cc9	0.69	0.19	0.69	0.19	0.78	0.18	1.10	0.13

Table 2 – Damage state dependent traffic closure times for each critical component of the network.

Critical component ID	Type	Traffic closure duration in days			
		DS ₁	DS ₂	DS ₃	DS ₄
cc1	Bridge	0	7	150	450
cc2	Bridge	0	5	100	200
cc3	Bridge	0	7	150	450
cc4	Bridge	0	7	150	450
cc5	Bridge	0	7	150	450
cc6	Bridge	0	5	100	200
cc7	Bridge	0	7	150	450
cc8	Tunnel	0	60	200	450
cc9	Tunnel	0	60	200	450
cc10	Bridge	0	7	150	450

unidirectional link along which it is located. As it is already mentioned, tunnel damage affects the network operation similarly to bridges depending on its own probability of failure (and link closure) given a suitable intensity measure, commonly permanent ground displacement, hence, equivalence between the intensity measures used for bridges and tunnels is required. In the following, a bridge or a tunnel is generally referred as critical component of the network.

4.2. Pre-earthquake traffic assignment

The pre-earthquake OD matrix was formed assuming a traffic demand of 1000 cars per hour for each of the node pairs (1,5), (5,1), (12,7), (7,12), (1,6) and (6,1). Zero demand was considered for the remaining node pairs. Travel paths corresponding to the fastest route for each of the non-zero demand node pairs are defined according to the link lengths, capacities and speed limits. As shown in Fig. 6, travel paths 1-8-10-9-4-5, 12-5-4-9-10-11-7 and 1-8-7-6 are used for satisfying demand associated to origin-destination pairs (1,5), (12,7) and (1,6), respectively, while the reverse paths are used for satisfying demand associated with reverse origin-destination pairs.

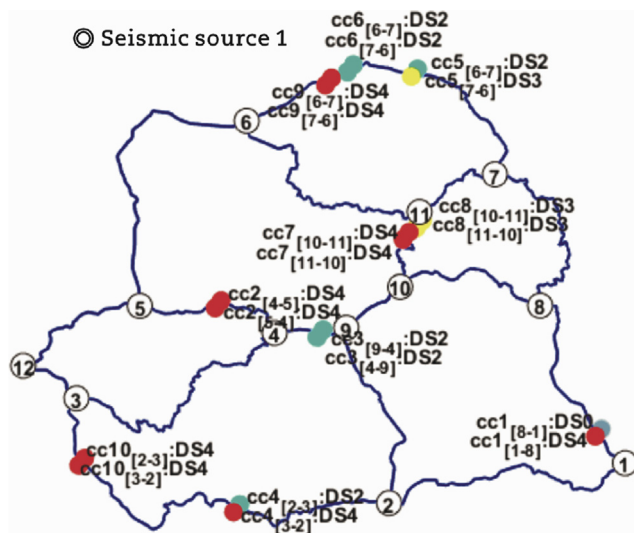


Fig. 7 – Damage sample s associated to seismic source 1 and recurrence period of 2000 years.

The average distance and speed before the earthquake are 64.25 km and 111.86 km/h, respectively.

4.3. Regional seismic hazard and fragility of critical components

The eight bridges were classified into three fragility classes, “MSC concrete”, “MSSS concrete” and “Box MSSS slab”, according to the classification system that was proposed by (Nielson et al., 2007).

Table 1 shows the classification of the 10 pairs of critical components assumed in the case study network into the four classes and the values of the parameters im_{mt} and β_t of the corresponding fragility curves for different damage states, i.e., DS₁ (minor), DS₂ (moderate), DS₃ (major) and DS₄ (collapse).

4.4. Post-earthquake traffic assignment

The restoration matrix is formed assuming that components classified to the same fragility class have the same traffic closure times. More specifically, for the classes 1 and 2 and for damage states DS₁ to DS₄, a traffic closure time of 0, 7, 150 and 450 days was assumed (Table 2). Similarly, for classes 3 and 4, traffic closure times were taken 0, 5, 100, 200 days and 0, 60, 200, 450 days, respectively. Since there is no overpass in the critical components of this case study the second restoration matrix is a zero matrix.

It is recalled that according to the methodology, the probability for each bridge to exceed a certain damage state given the intensity measure at the specific site of interest in a seismic map, leads to a Monte Carlo analysis and the corresponding initial damage distribution samples. Based on the restoration matrices, post-earthquake damage distribution samples are then analyzed into recovery phases to account for the gradual restoration of network functionality. Each recovery phase is coupled with a post-earthquake OD matrix to form a traffic scenario.

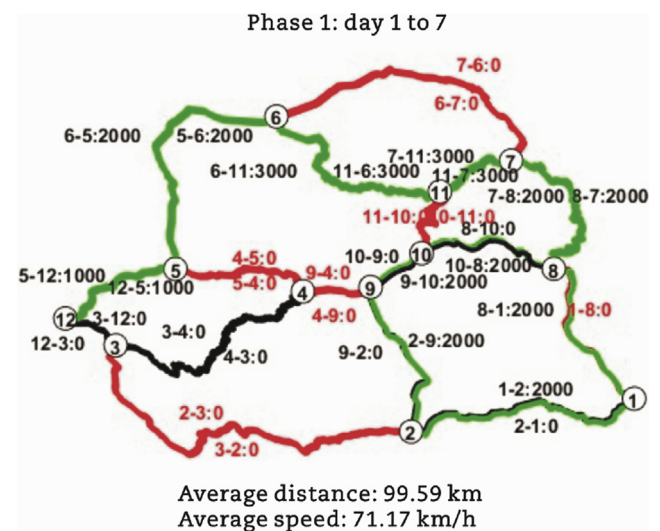


Fig. 8 – Traffic map for the first recovery phase associated to damage sample s .

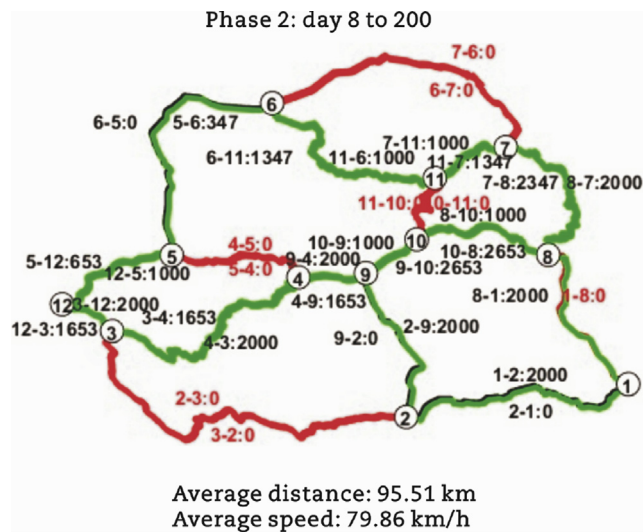


Fig. 9 – Traffic map for the second recovery phase associated to damage sample s.

4.5. Reference traffic analysis for earthquake-independent OD matrix

As a reference case, the OD matrix is assumed to be earthquake-independent, that is, the post-event OD matrix is equal to the pre-event matrix. Fig. 7 shows an indicative damage sample that is decomposed into three phases as well as the traffic flows of the corresponding traffic scenarios. In red are the links that are closed due to closed critical components, in green the links that are not affected by closed critical components and serve as part of a post-quake driving routes and in black are the links that are not affected by closed critical components but do not serve as part of a post-quake route. It is noted that for phase 1, that corresponds to the time span between 1st and the 7th day after the earthquake, the average distance traveled by the network users is increased from the pre-earthquake value of 64.25 km–99.59 km due to the increased length of the

alternative routes followed after the earthquake. Notably, for phases 2 and 3 it drops to 95.51 km and 74.29 km, respectively, while it is restored back to its pre-earthquake value by the end of the 3rd phase, which corresponds to the 450th day after the earthquake event.

On the other hand, average travel speed drops drastically immediately after the earthquake from 111.86 km/h to 71.17 km/h. This drop is attributed to the increased use of secondary roads that have lower speed limit. The driving speed is further reduced due to the higher congestion that is associated to the lower traffic capacity of the secondary roads. Similarly, to the total distance traveled, driving speed gradually returns back to its pre-earthquake value. Increased distances and decreased driving speeds lead to a variation of the traffic cost that is eliminated by the end of the recovery period as shown in Fig. 11. It is noted that traffic variation is derived herein by multiplying travel time variation with a nominal value of time that is taken equal to 7.3 €/day.

Two expansion factors are also used for converting the 1 h flow derived by the traffic assignment to a 24 h flow of a typical day. The first one is related to the transformation of the hourly flows to daily flows and equals to 16.08. The second expansion factor is related to the transformation of the flows derived for the analysis day to the typical day of the year and equals to 1.18. Cost of cancelled trips is assumed zero throughout the recovery period because, for this specific network, each pre-earthquake route has an alternative one that is utilized after the earthquake.

5. Sensitivity analysis

In this section, the impact of four different assumptions for the post-earthquake demand variation on the time-variant and cumulative cost is investigated, inclusive of the reference one presented in section 4.5. All cases are based on the multiplication of the pre-quake OD matrix with a phase-dependent reduction OD factor. A summary of the four alternative assumptions regarding OD time evolution is given below.

- Earthquake-independent OD: it is assumed that traffic demand is unaffected by the earthquake, hence, the post-event OD matrix is taken equal to the pre-event matrix as described in section 4.5.
- Earthquake- and time-dependent OD: it is assumed that immediately after the earthquake, the vehicle numbers prescribed in the OD matrix are multiplied by a standard factor of 0.4 assuming spatially uniform traffic reduction of 60%. Traffic (and the corresponding multiplication factor) gradually increases at the end of each phase proportionally to the corresponding time instant and it is restored back to its initial state by the end of the recovery phase.
- Earthquake-dependent/time-independent OD: similarly to (b) with the use of the mean OD factor for simplicity.
- Earthquake-, time- and functionality restoration-dependent OD: corresponds to the approach presented in section 2.3 where OD matrix evolves in time based on the time-variation of the network disruption index.

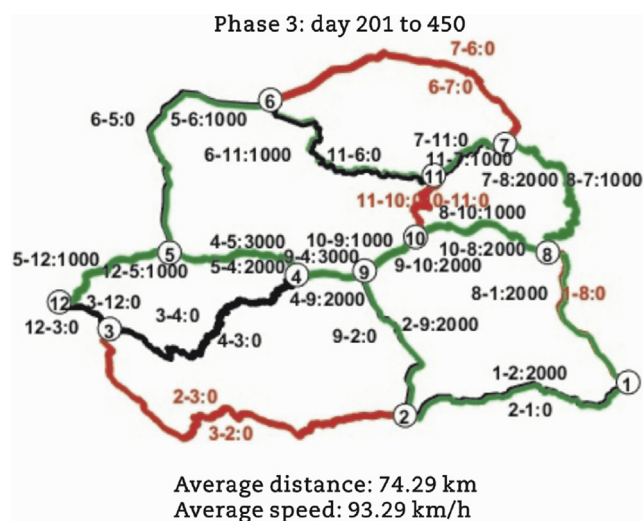


Fig. 10 – Traffic map for the third recovery phase associated to damage sample s.

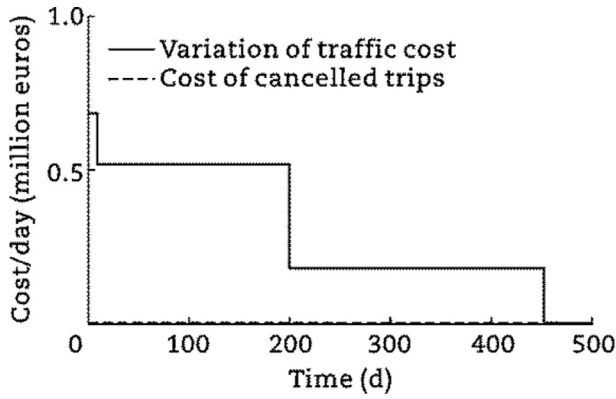


Fig. 11 – Phase-dependent variation of traffic cost and cost of cancelled trips.

Fig. 12 shows the value of the OD factor for the 3 phases shown in Figs. 8–10 and for each one of the four assumptions examined. Fig. 13 further illustrates the phase-dependent variation of the traffic cost. It is noted that the time-dependent OD assumption of case (b) and the time-independent OD assumption of case (c) include negative variations of the traffic cost which means the post-earthquake travel cost is lower than the pre-earthquake cost during a part of the recovery period. This happens because, in these cases, the post-quake traffic cost is indeed increased due to rerouting and the associated increase in the average trip time, but at the same time it is reduced due to trip cancellations that occur as a result of the reduced traffic demand introduced by means of the OD reduction factor. Note that in this case, the actual cost of the impact of canceling a trip is not considered. It is the traffic (driving) cost that it is implicitly affected by skipping a trip.

Fig. 14 depicts the actual cost of the cancelled trips, on the basis of a nominal cost of 20 € for each cancelled trip. It is noted that cancelled trips are generally attributed to the fact that a destination is inaccessible or undesirable after an earthquake, or to the reduced post-quake demand as a whole. As anticipated, this cost is zero for the earthquake-independent OD given that no trips are cancelled in this case and constant for the time-independent OD case. Out of the remaining two, the NDI-based (i.e., functionality dependent) OD matrix provides a more realistic estimate.

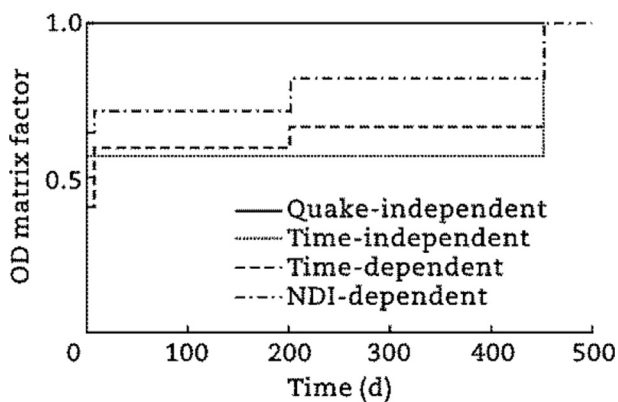


Fig. 12 – Phase-dependent pre-quake OD matrix factor.

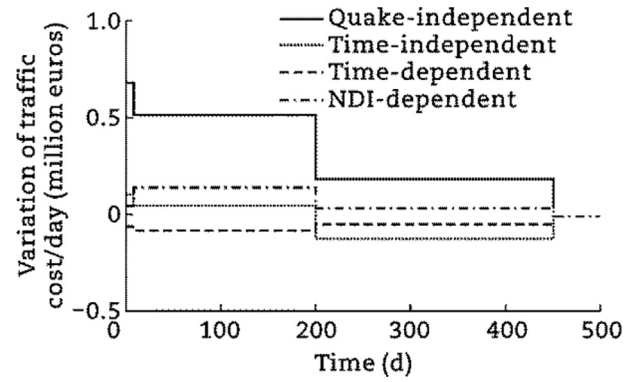


Fig. 13 – Variation of traffic cost vs time.

To account for the total traffic cost due to the earthquake, the variation of the traffic cost is integrated through the entire recovery period, resulting to the cumulative variation of the earthquake-induced traffic cost (CVTC) with respect to the initial, pre-earthquake, traffic cost. More precisely, for the S damage distribution samples that correspond to the different earthquake scenarios examined, S values for the cumulative variation of the traffic cost are derived. Fig. 15 shows the mean of these estimates of the CVTC for four common earthquake scenarios with a recurrence period of 500, 1000, 1500 and 2000 years (note that the longer the return period, the higher the intensity of the earthquake). It is observed that in all cases, the cost increases with the intensity of the earthquake (i.e., positive variations increase and negative variations decrease).

It is also seen that the quake-independent OD leads to a significantly higher cost (90, 140, 160 and 180 million € for the earthquake scenario with 500, 1000, 1500 and 2000 years recurrence period, respectively). This is observed irrespective of the earthquake scenario examined and clearly indicates that the assumption that traffic is not altered after the earthquake might lead to significantly higher and unrealistic estimates of the earthquake-induced traffic cost.

The simple assumption of a time-dependent OD and the even simpler, time-independent OD, lead to negative variations of cost compared to the pre-earthquake traffic cost due to the dominant influence of trip cancellations, as explained previously. The NDI-dependent OD assumption on the other

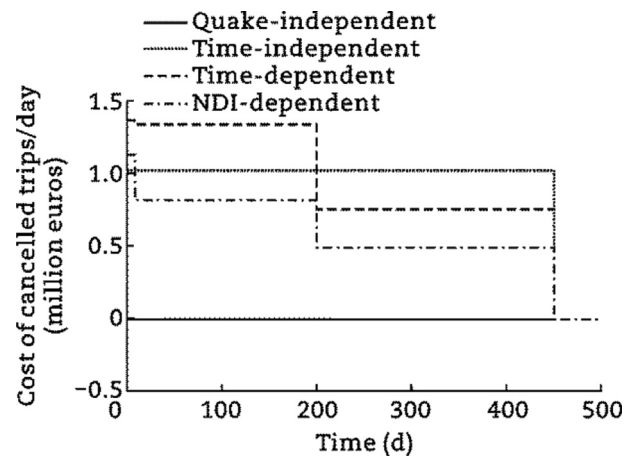


Fig. 14 – Cost of cancelled trips vs time.

hand, is the one that yields the most reasonable prediction since it considers the reduced traffic due to trip cancellations, the functionality of the network but also the importance of the links that are closed and gradually recovered. In this case, the associated traffic cost is 10 million € for the frequent event with a recurrence period of 500 years. Fig. 16 shows, in absolute terms, the cumulative cost of cancelled trips (CCCT) that is derived similarly to the cumulative variation of the traffic cost (CVTC). Again, the quake-independent OD is associated to zero number of cancelled trips. Time-dependent and time-independent OD matrices lead to significant costs of cancelled trips that exceed the 400 million €. It is worth mentioning that in these cases, the cost is practically unaffected from the earthquake intensities which is deemed non-realistic. On the other hand, the cost of cancelled trips for the NDI-dependent OD factor increases with the recurrence period (190, 280, 295 and 320 million € for the earthquake scenario with 500, 1000, 1500 and 2000 years recurrence period, respectively).

Fig. 17 illustrates the total earthquake cost, which is the sum of the cumulative variation of traffic cost (CVTC) due to rerouting and reduced number of trips, the pure cumulative cost of

cancelled trips (CCCT) and the total structural cost (TST) associated with damage rehabilitation across the network as derived by means of restoration curves relating a damage state with a repair cost for different structural typologies. As previously, the time-dependent and time-independent OD lead to similar costs for the four recurrence periods but tend to be earthquake-intensity independent which indicates that they do not consist a reliable proxy of earthquake impact.

For the earthquake-independent OD the total cumulative cost is 100, 145, 165 and 190 million € for the earthquake scenario with 500, 1000, 1500 and 2000 years recurrence period, respectively. These values are slightly higher than the respective cumulative variation of traffic cost values as they only include the structural cost (direct trip cancellation costs being zero). For the NDI-dependent OD the total earthquake cost increases significantly with earthquake intensity (210, 310, 350 and 380 million € for the earthquake scenario with 500, 1000, 1500 and 2000 years recurrence period). In comparison to the earthquake-independent OD it is clearly superior as the latter entirely misses the direct cost of trip cancellations as it assumed that OD remains constant before and after the earthquake event.

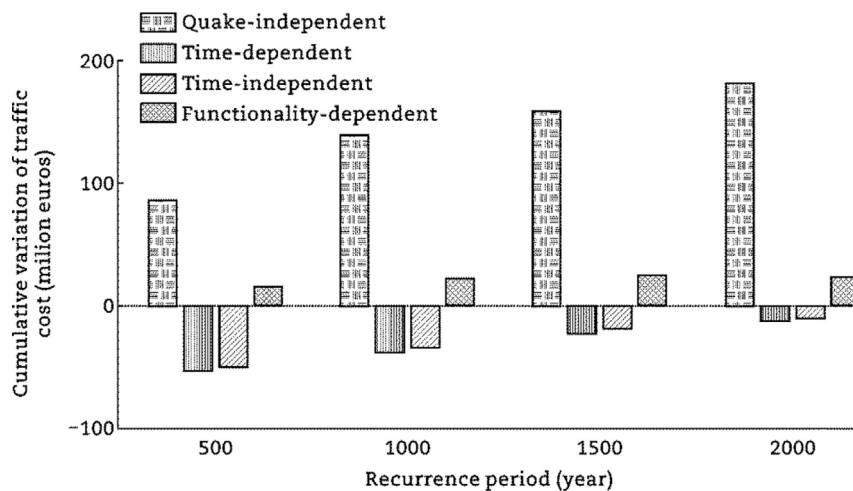


Fig. 15 – Cumulative variation of traffic cost (CVTC) with respect to the initial (pre-earthquake) traffic cost.

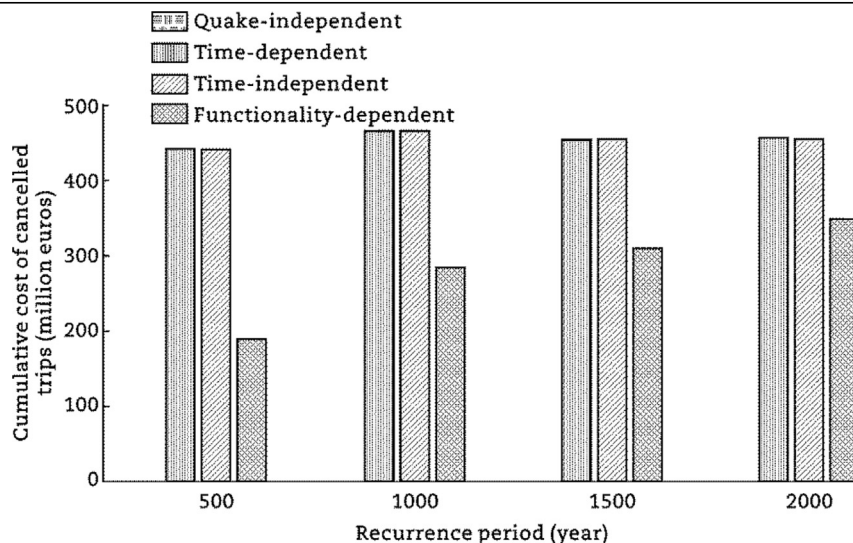


Fig. 16 – Cumulative cost of cancelled trips (CCCT).

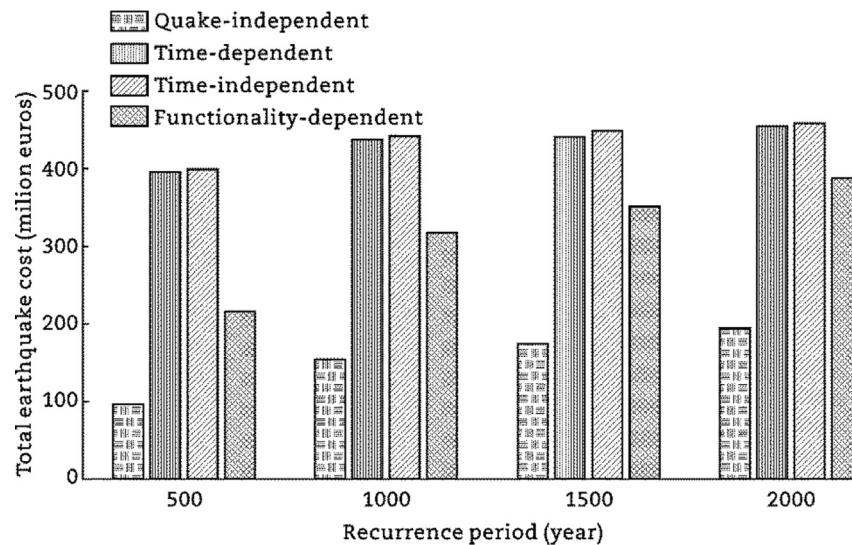


Fig. 17 – Total earthquake cost (TEC).

The NDI-dependent OD is also superior to the other two assumptions as it is sensitive to the intensity of the earthquake. Overall, it is evident that a realistic representation of the evolution of traffic demand after the earthquake and during the recovery period plays a major role on the final estimate of the total earthquake cost in a highway network.

6. Conclusions

In this paper an existing framework for assessing the seismic risk and resilience of road networks in earthquake prone areas is extended to incorporate the impact of the post-earthquake traffic demand variation on the overall cost, as this arises from altered post-earthquake travel times and trip cancellations. Traffic data such as pre- and post-earthquake routes, flows and speeds are explicitly taken into consideration by convoluting seismic hazard, fragility, restoration and traffic analyses. Considering a case study network, four different assumptions are made regarding the traffic demand evolution from the onset of the earthquake to the end of the recovery period. The results, consisting of a broad range of cost indicators, highlight the necessity to account for a dynamic (i.e., time evolving) origin-destination matrix in the post-earthquake traffic analyses conducted as part of the highway network resilience quantification. They also highlight the importance of quantifying the cost related to both travel time variations and trip cancellations since they cumulatively constitute the biggest part of the total earthquake losses being notably larger than the structural cost. It is also shown that not all post-earthquake traffic demand assumptions are equally efficient in capturing the dynamic interplay between earthquake intensity, network functionality, trip rerouting and cancellation and the ultimate earthquake-induced traffic cost while traffic demand assumptions based on the time-varying network functionality indicators seem to be more efficient. Future research is needed particularly by processing traffic data after real earthquakes together with behavioral models that realistically predict the drivers' response at the onset of a major earthquake and beyond.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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